Rapid Response to Department of Defense (DOD) Needs using HPC Capabilities

by

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Abstract

Approximately one-fifth of the Pentagon has recently been renovated including improvements to the blast resistance of the exterior walls and windows. Post-event investigations have indicated that these improvements saved lives during the September 11, 2001 aircraft impact on the Pentagon. The U.S. Department of Defense (DOD) desires to quickly rebuild the area of the Pentagon damaged in the terrorist attack, but wants to consider improvements to further enhance safety of Pentagon occupants. The ERDC was asked to conduct a 30-day study to evaluate enhanced retrofit concepts. The ERDC has developed High-Performance-Computing (HPC) techniques required to analyze the Pentagon structure and requested and received high-priority HPC processing time. Because of the availability of high-priority HPC processing time and validated HPC methodologies, the ERDC was successful in completing this 30-day study and presented the results to the Pentagon Renovation Office (PenRen). The PenRen has requested that ERDC perform more specific studies based on the results of the 30-day study.

Introduction

The layout of the Pentagon is shown in Figure 1. The Pentagon consists of five concentric rings (A-E) connected by radial corridors. The lightwells between rings B and C extend to the first floor of the Pentagon. The remaining lightwells extend down to the roof of the second floor. The planned renovation of the Pentagon is to be conducted in five phases. For this purpose, the Pentagon was divided into five wedges. Wedge 1 extends from the center of Section (side) A to the center of Section B. Renovations to Wedge 1 were very nearly complete on September 11, 2001.

The Wedge 1 renovations included enhancements to the blast resistance of the exterior walls and windows of the Pentagon. The exterior windows were replaced with thick, insulated/laminated windows designed to resist significant blast loads. The Pentagon is a concrete frame structure with a double layer brick wall clad with large limestone blocks serving as the exterior wall of the Pentagon. This wall is incapable of supporting the reactions from the blast-resistant windows. Therefore the original blast retrofit included a system of vertical structural steel tubes that transfers these reactions to the floor slabs of the Pentagon (Figure 2). Horizontal tubes support the top and bottom of the window. Geotextile fabric was installed behind the brick wall to catch the debris that would be caused by the failure of the brick wall. The fabric was attached to the floor slabs and to the horizontal tube beneath the window.

On September 11, 2001, a terrorist-controlled aircraft crashed into Wedge 1, close to the Wedge 1-Wedge 2 boundary. Post-event damage is shown in Figure 3. The Wedge 1- Wedge 2 boundary is at the center of the radial corridor about 135 ft to the left of the impact area. The response of an original Pentagon window is shown in Figure 4. This window was located 295 ft north of the impact area and indicates a high hazard to room occupants. A retrofitted window located 55 ft north of the impact area is shown in Figure 5. This window was not a hazard to room occupants. This pair of windows demonstrates that, even though the retrofits were designed to resist blast loads, they were effective in saving lives in the September 11 event.

The DOD desires to quickly rebuild the damaged section of the Pentagon and to evaluate the retrofit techniques being used. The U.S. Army Corps of Engineers led an effort to evaluate the retrofit methods being used and to consider alternate retrofits that might provide an even greater level of protection. The Geotechnical and Structures Laboratory (GSL) of ERDC led the evaluation of the blast resistance of the existing Pentagon, the Wedge 1 retrofit, and proposed enhanced retrofit concepts. The GSL also considered other blast related issues. One of these issues is the effect of the blast environment to parts of the Pentagon other than the outside of the outermost ring. Of particular interest is the blast response of the windows in the lightwells due to blast caused by the detonation of a large truck bomb placed outside of the Pentagon. Because of the urgency of rebuilding the Pentagon, the study had to be completed in 30 days.

The GSL has developed HPC methods of predicting the response of window systems and masonry walls to blast loads. The methods have been evaluated against experimental data, and code scalability studies have been performed. Priority HPC resources were requested and granted by the High Performance Computing Modernization Office (HPCMO) on the Origin 3000 and IBM SMP systems at the ERDC Major Shared Resource Center (MSRC).

Objectives

The first objective of the study was to evaluate the safety of occupants of the original non-retrofitted Pentagon for a range of threat conditions. The next objective was to evaluate the retrofit previously installed in Wedge 1. The third objective was to develop, analyze, and evaluate alternate retrofit methods to improve the safety of Pentagon occupants. The last objective of the research presented in this paper was to demonstrate that significant blast pressures can propagate into the lightwells and that the blast responses of those windows need to be evaluated.

Approach

A common approach for evaluating the blast response of structures is to develop a pressure-impulse (P-I) diagram such as the one shown in Figure 6. Each point on the curve represents equivalent damage to the structure. For example a P-I diagram could be developed to predict failure of a wall. Using the P-I diagram, the analyst simply computes the pressure and impulse associated with the explosive weight, standoff, and angle of incidence. If that pressure-impulse combination falls above or to the right of the curve, failure of the structure is predicted. P-I diagrams are typically generated by performing a large number of single degree of freedom

(SDOF) analyses to converge on a series of pressure-impulse pairs that cause the desired amount of damage.

P-I diagrams are easily generated for simple structures that can be represented as an SDOF system. The Pentagon wall and window systems do not fall into this category. In one of the window retrofits being developed, HPC simulations were used to develop a resistance function. That resistance function was then used in SDOF analyses to develop a high-hazard P-I diagram for that window retrofit. The Pentagon exterior wall is a very complicated structure whose response depends on the interaction of a two-layer brick wall with a layer of limestone blocks, the window, and the concrete frame structure. The approach selected in this case was to approximate the resistance of the system as the sum of the resistances of the different components. That resistance function was then used to determine P-I diagrams to predict light, moderate, and heavy damage for the original Pentagon exterior wall. Finite element (FE) analyses were performed to validate the P-I diagrams. This procedure was repeated for the original retrofit of the Pentagon and two enhanced retrofit designs. The HPC simulations were performed using the HPCMP Common HPC Software Support Initiative (CHSSI) Computational Structural Mechanics (CSM) FE code, ParaDyn (Hoover, DeGroot, and Pocassini, 1995), and the serial version, DYNA3D (Whirley and Engleman,1993) of that code.

Under Challenge Project C83, "Blast and Barrier Design for Urban Terrain," (Armstrong, et al 2002) the GSL is using the CSM computer code SHAMRC (Crepeau, 1998) to predict the effects of buildings on the loads on surrounding buildings. The propagation of blast into the lightwells is similar to the propagation of blast around or over a structure. A simulation was performed using SHAMRC to predict blast loads in the lightwells of the Pentagon.

Resistance Function for 1-in. Polycarbonate Window with Muntin

The GSL had previously conducted analyses and experiments to develop and validate a large window constructed using 1-in.-thick polycarbonate supported by the window frame and a horizontal and vertical muntin system (O'Daniel and Dinan, 2001). The FE model of the system is shown as Figure 7. Analyses were performed using ParaDyn on the ERDC Origin 3000. Pre-test predictions of displacements of the center of the muntin are compared with experimental data in Figure 8. The predictions matched the experimental data very well, validating the analysis methodology. Analyses of a muntin system developed for the Pentagon window were performed to determine the static resistance function of that system. Since the desired result is a static resistance function, rate effects were turned off in these analyses. The loading on the system was ramped up from zero to the maximum load. In the initial analyses the load was increased at a rate of 100 psi/ms. The load rate was then decreased (to 10 and 1 psi/ms) until the resistance function converged. As seen in Figure 9, there is very little difference in the resistance function for the second (PResist5) and third (PResist6) runs except for very near failure (the end of the resistance function). That resistance function was used to develop the high-hazard resistance function used to evaluate that window against several weapon threats (Hall, et al, 2002).

Methodology for Prediction of Masonry Wall Response

A methodology for predicting the response of concrete masonry unit (CMU) walls has been developed (Dennis, et al 2002, O'Daniel, et al 2001) and validated against experimental data. The method uses the FE code ParaDyn. In this method each CMU is discretized into hexahedral elements. Each CMU is connected to its neighboring CMUs using tie-breaking interfaces. The tie-breaking interface behaves as a tied surface until the failure criterion is met. Once the criterion is met the interface acts a general contact surface that can separate and slide with friction. The ParaDyn scalable algorithms are designed to divide the problem mesh into sub-domains. Solutions on sub-domains are connected together by communicating data across processors along the boundaries of the sub-domains. A pre-processing code takes the original entire mesh and attempts to balance load among processors by assigning elements to each of the processors. Shared nodes along boundaries are duplicated in all processors containing elements attached to those nodes.

A scalability study was conducted for a one-block-wide model, Figure 10. The model is 19 blocks tall and each layer is tied together using a tie-breaking surface. Every other layer consists of two half blocks that are tied together using tie-breaking surfaces. Contact surfaces such as these significantly affect partitioning and scalability. The model consisted of about 49,000 nodes and 29,000 continuum elements. Each of the simulations was identical except for the number of processors used. Because of the small number of nodes and elements involved, scalability beyond 32 processors was not evaluated.

The results of the scalability studies are shown as Figures 11 and 12. The computational time shown is the maximum processor time used by any of the processors. The actual performance is compared to ideal scalability. The ideal scalability curve was determined by dividing the time required for two processors by the number of processors used and then multiplying by two to get scalability related to a single processor. Although scaling between two and four processors is good, scaling beyond four processors is not as good for the CMU problem. For perfect scaling, the time required for the simulation should be inversely proportional to the number of processors. The speed factor shown in Figure 12 is the time required for a single processor (taken as twice the time for two processors) divided by the time required for the number of processors under consideration.

Pentagon Wall Model

A two-layer brick wall fills the area between concrete columns in the exterior wall of the Pentagon. The FE model of the original Pentagon exterior wall, Figure 13, takes advantage of symmetry through the center of the window, as well as through the center of the column. Thus only half of the wall (starting at the center of the column and going to the center of the window) needs to be modeled. The model includes the floor slabs above and below the wall, half the width of the column, the brick walls, and the limestone cladding on the outside of the wall. Each brick is modeled using hexahedral elements. The bricks are tied together using tie-breaking interfaces. The friction coefficient was conservatively taken as 0.3. Tie-breaking surfaces were used to tie the bricks to the floor slab below, the edge beam above, and the concrete column on the left of the model. The large limestone blocks were also tied together using tie-breaking interfaces. The general sliding with friction slide surface type was used in areas of the model where contact was expected. For example a slide surface was used to prevent the limestone blocks from penetrating through the brick wall, the column, and the floor slabs above and below. A slide surface prevented one brick wall from penetrating through the other. Approximately 150,000 elements were required to model the original Pentagon wall. Although the model would partition well on up to eight processors, analyses could not be performed on the parallel code ParaDyn and all of the simulations were performed using the serial version, DYNA3D, of the code. A 200 msec simulation required about 24 processing hours on the ERDC Origin 3000.

The FE model of the original Pentagon retrofit is shown as Figure 14. Structural steel tubes, the window, and geotextile fabric have been added to the model of the original wall. In this retrofit design, the window is designed to survive. The window will transfer loads to the structural steel tubing. The structural steel tubing affects the response of the wall and since the window affects the tubing response the window must be modeled. The window glazing and window frame are modeled using shell elements. The structural steel tubing is modeled using shell elements. Slide surfaces are added to prevent the brick wall from penetrating the steel tubing and to prevent the brick wall from penetrating the geotextile fabric. The fabric is attached to both floor slabs and to the horizontal tubing below the window. The first enhanced retrofit concept involved replacing the geotextile fabric with a steel liner. That simply involved changing the material properties of the shell elements. The second enhanced retrofit involved using a thicker metal liner and thicker structural steel tubes. Again this was a matter of changing the material properties. In the second enhanced retrofit, the horizontal steel tubes were extended to the concrete columns. The retrofit analyses required about 8 processor hours for a 50 ms simulation

In each analysis a pressure loading was applied to the outer surface of the limestone cladding. For each P-I diagram to be evaluated, two categories of loads were applied. An impulsive load (high-pressure, short duration) and a low-pressure instantaneously applied constant load were applied. This is an attempt to validate the pressure and impulse asymptotes of the P-I diagram (Figure 6). An example of the response of the un-retrofitted Pentagon wall is shown as Figure 15. The brick wall fails at a high velocity and would represent a high damage to building occupants. A retrofitted wall response is shown in Figure 16. Although the brick wall fails, the debris is captured by the geotextile fabric and is not a hazard.

Finite element results are compared with P-I diagrams for the non-retrofitted, original retrofit, and two modified retrofits are provided in Figures 17-20. These figures show that the approximations used to develop the P-I diagrams are adequate and these P-I diagrams were used in the study.

Blast Propagation into Lightwells

Blast propagation analyses were performed for a specific charge weight at a given critical charge location. The analyses were performed using the SHAMRC code. The code and modeling methods have been validated against experimental data (Armstrong, et al, 2002). The model consisted of about 65 million cells. The analysis simulated about 240 msec and required 18,000 processors of the ERDC IBM SMP. As many as 95 processors were used. The shock front location at 150 msec is shown as Figure 21. This figure shows that the shock propagates down into the lightwells and will load the windows. Blast load histories are being compared with window capacities to determine if there is a hazard to building occupants.

Summary and Conclusions

Because of the availability of high-priority HPC processing time and validated HPC methodologies, the GSL was successful in completing this 30-day study and presented the results to the Pentagon Renovation Office (PenRen). PenRen has requested that GSL perform more specific studies based on the results of the 30-day study. HPC simulations are being used to improve the safety of Pentagon occupants during a terrorist attack.

Acknowledgements

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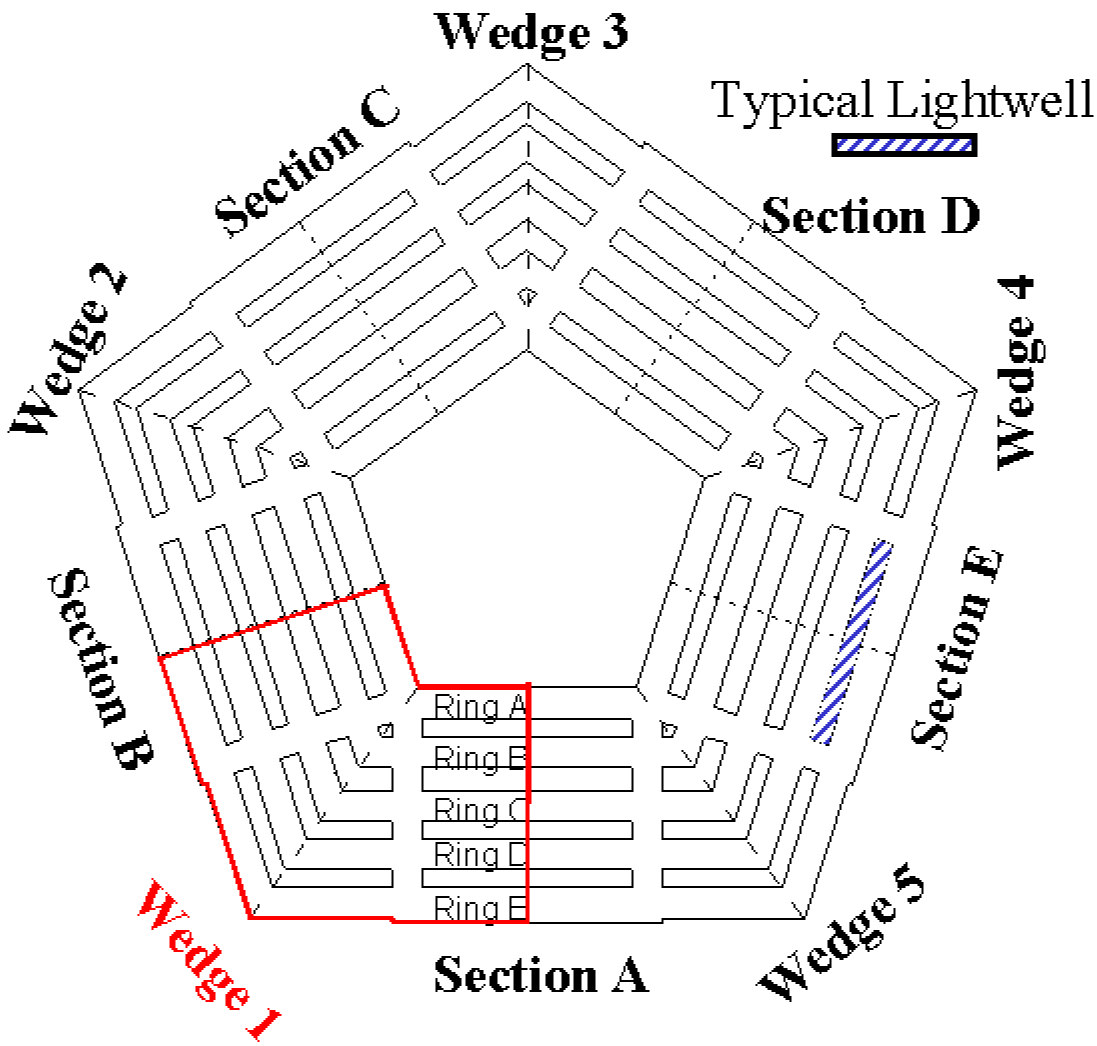

Figure 1. Pentagon layout

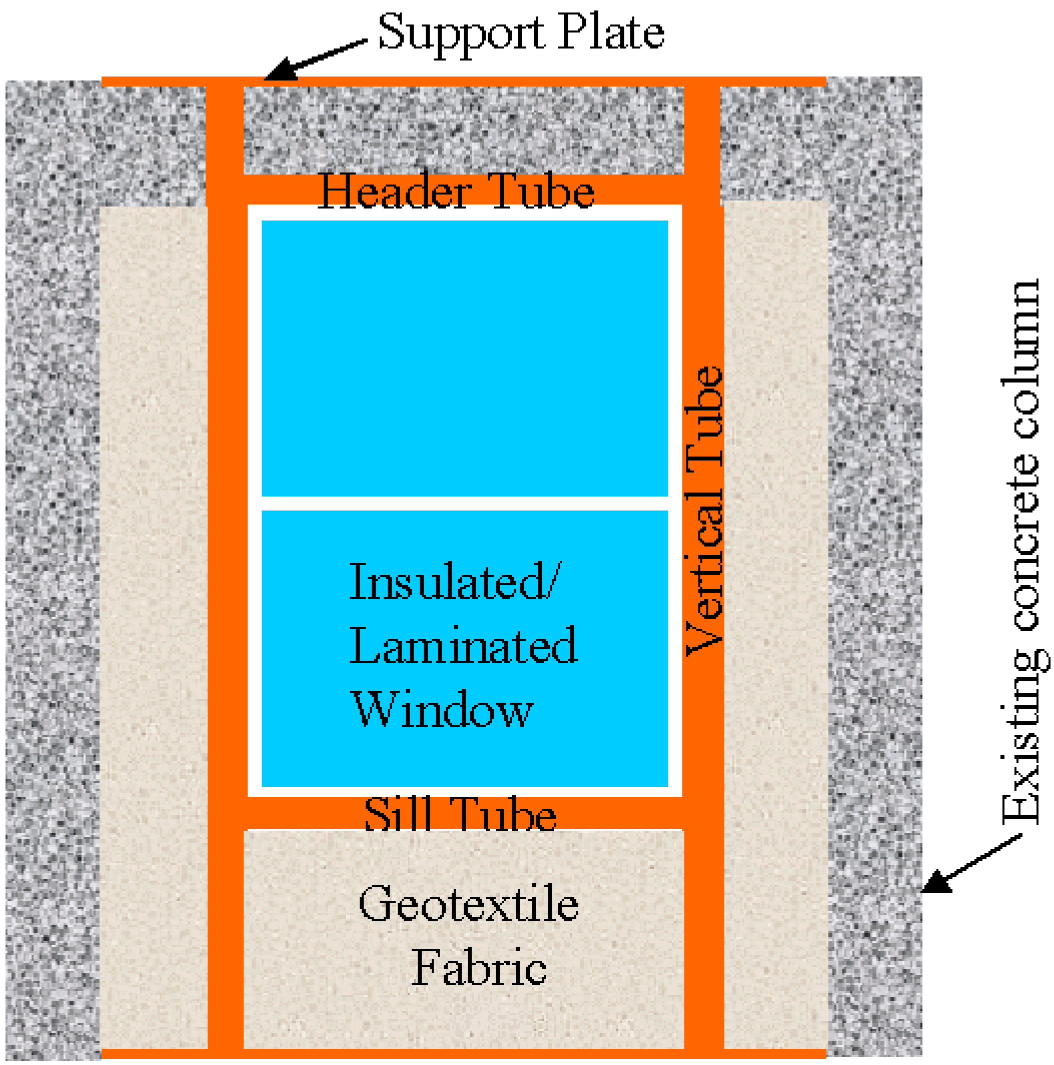

Figure 2. Current retrofit

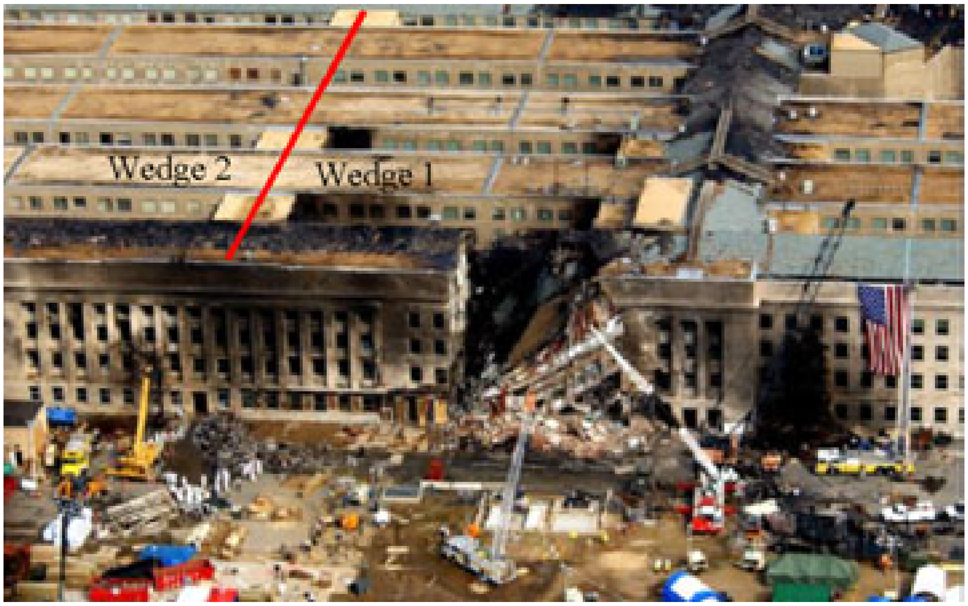

Figure 3. Damage after September 11, 2001

Figure 4. Non-retrofitted window 295 ft north of impact

Figure 5. Retrofitted window 55 ft north of impact

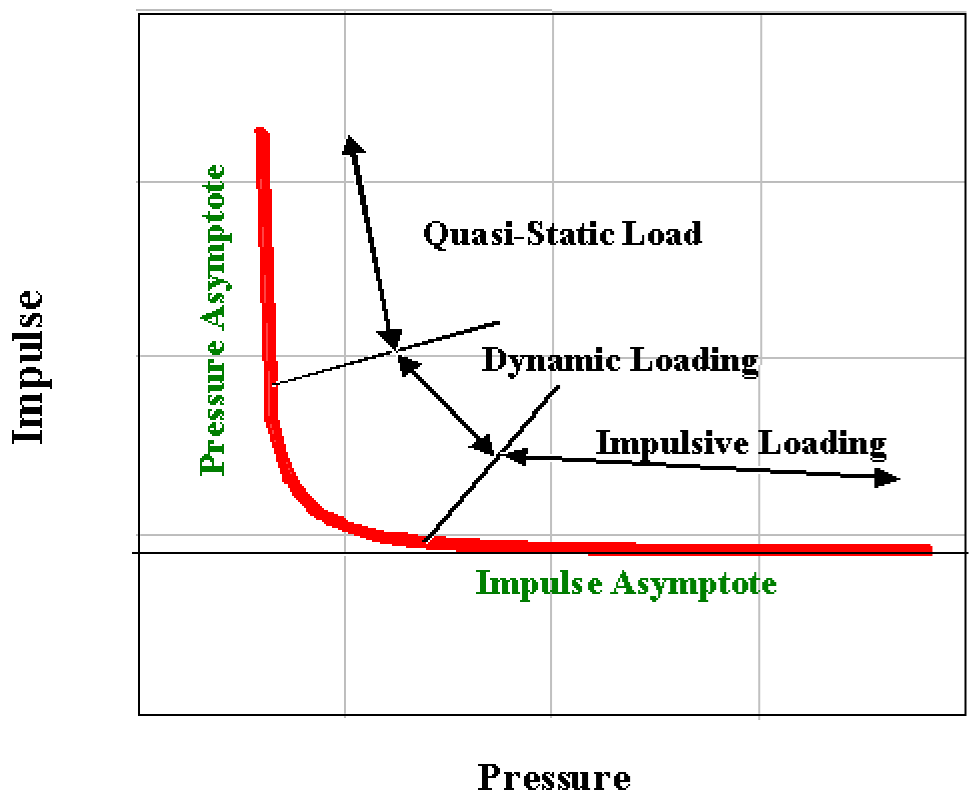

Figure 6. Pressure-Impulse (P-I) diagram

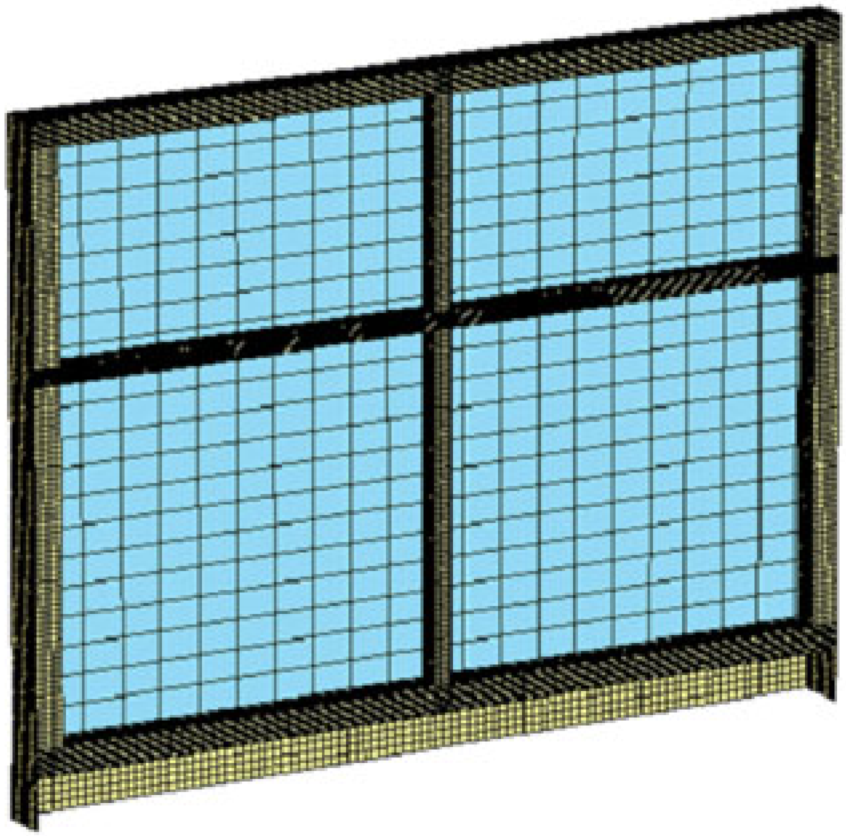

Figure 7. FE model of window with muntin

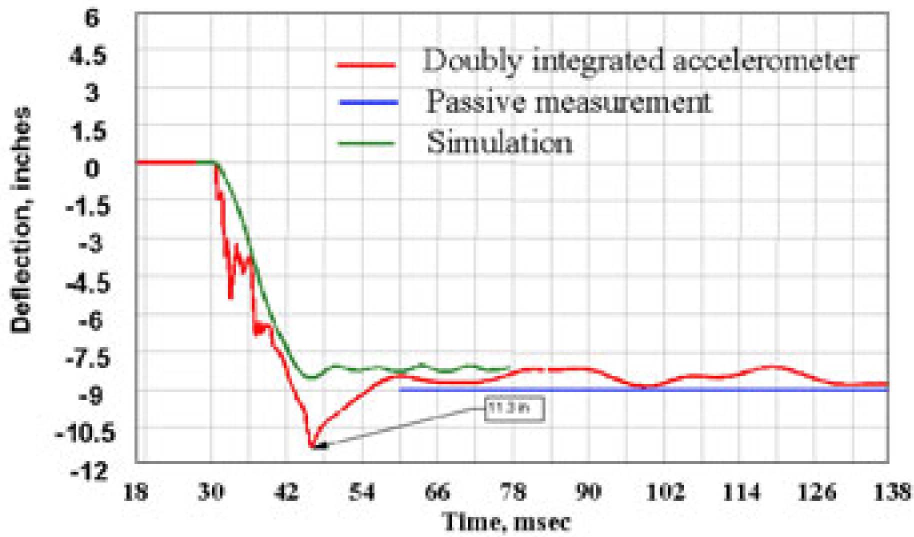

Figure 8. Displacement of center of muntin

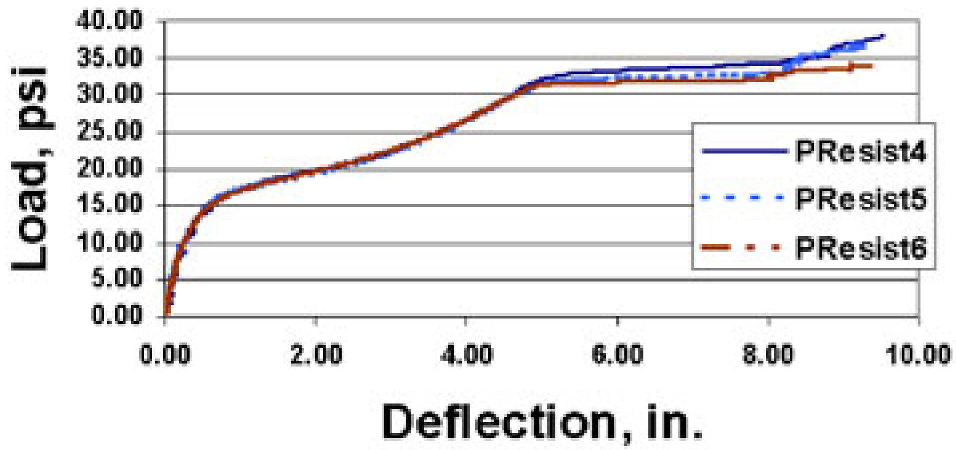

Figure 9. Muntin window resistance functions

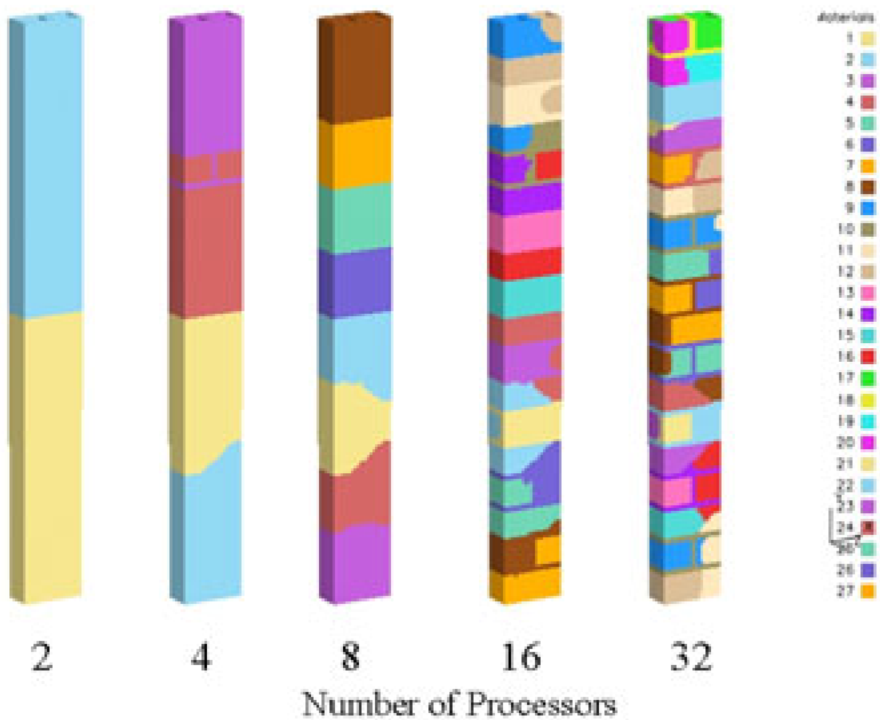

Figure 10. Partitioning of single block wide CMU wall

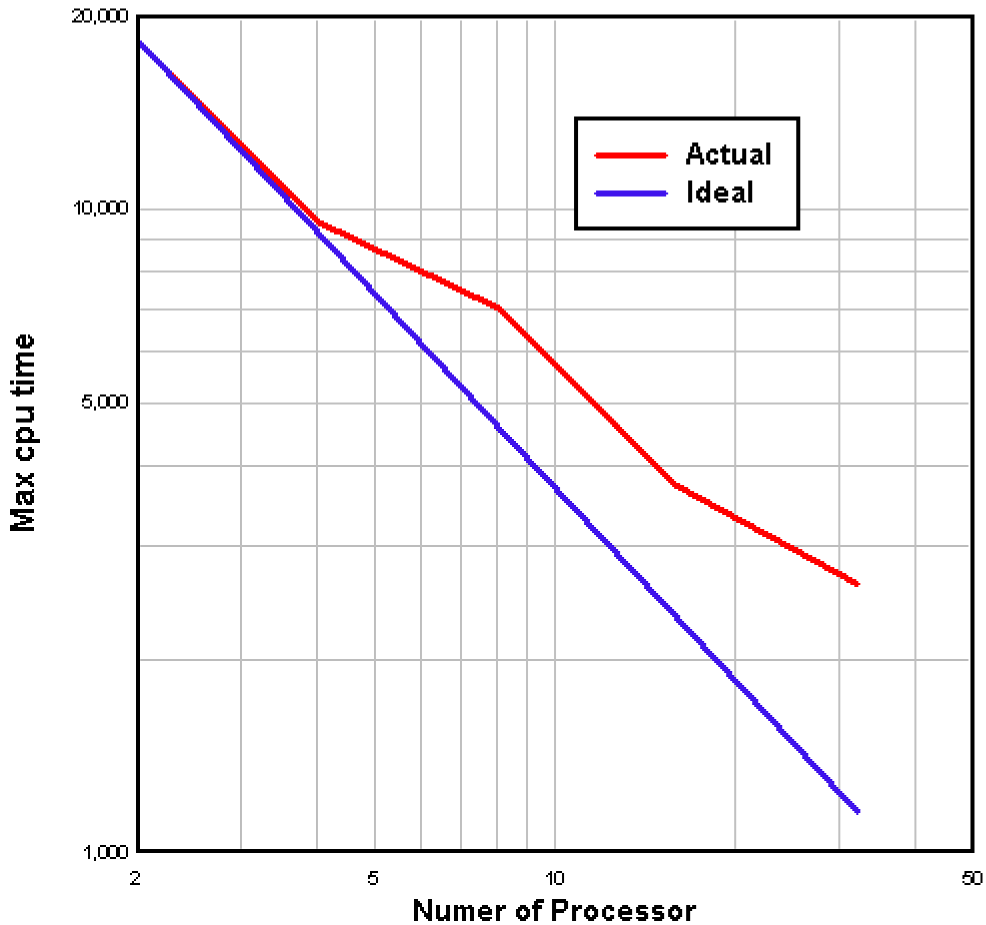

Figure 11. Maximum processor time, sec

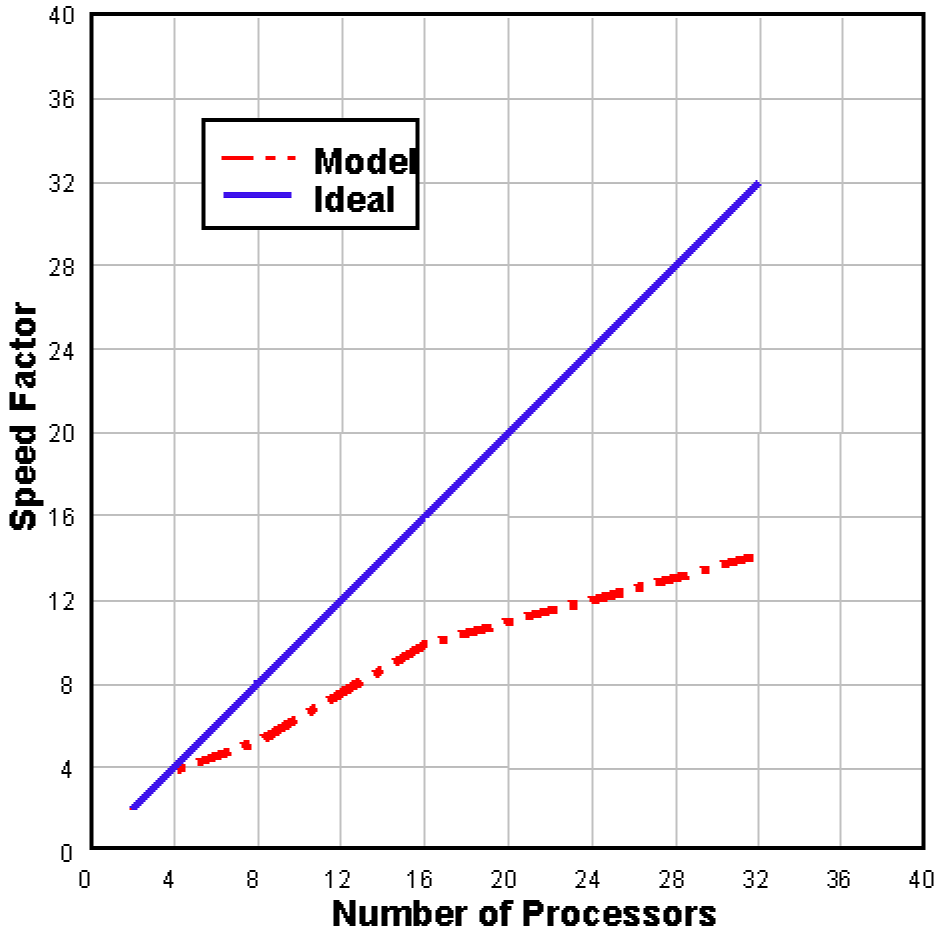

Figure 12. Speed factor

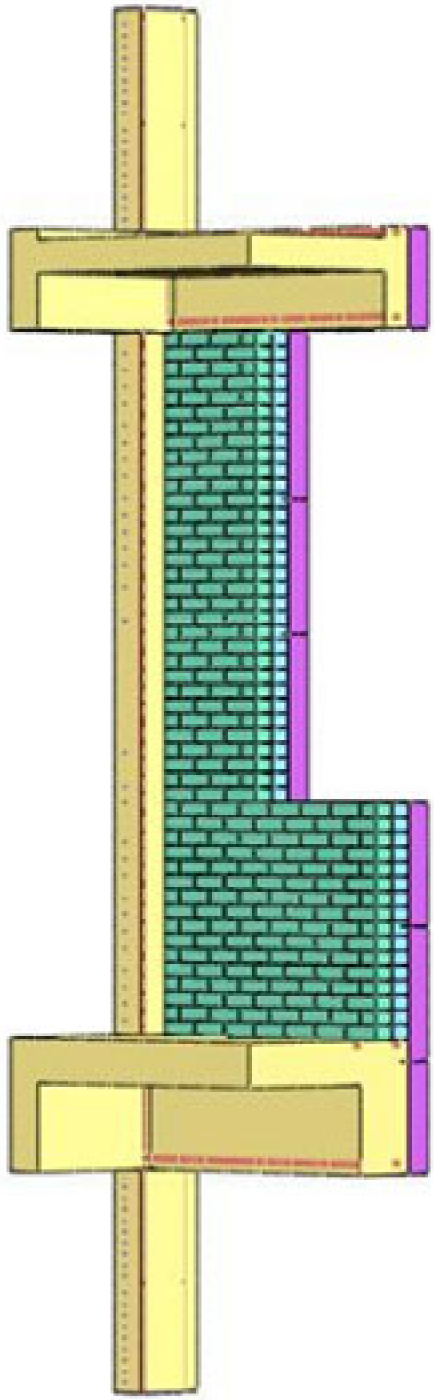

Figure 13. Original Pentagon wall model

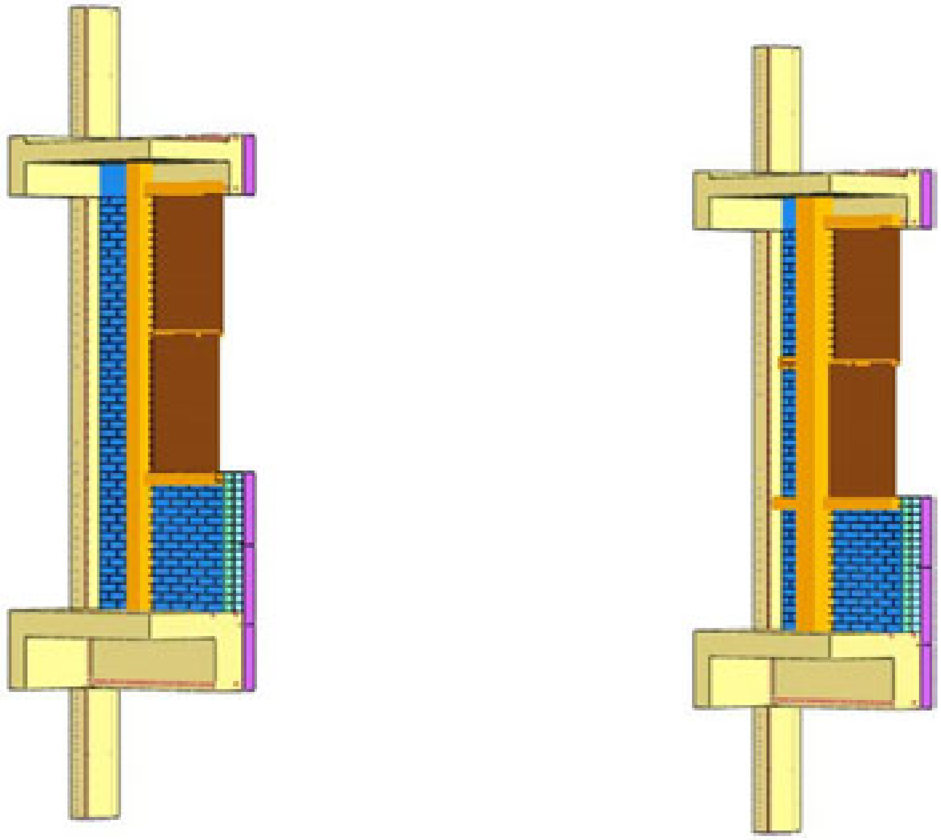

Figure 14. Original and second enhanced retrofitted walls

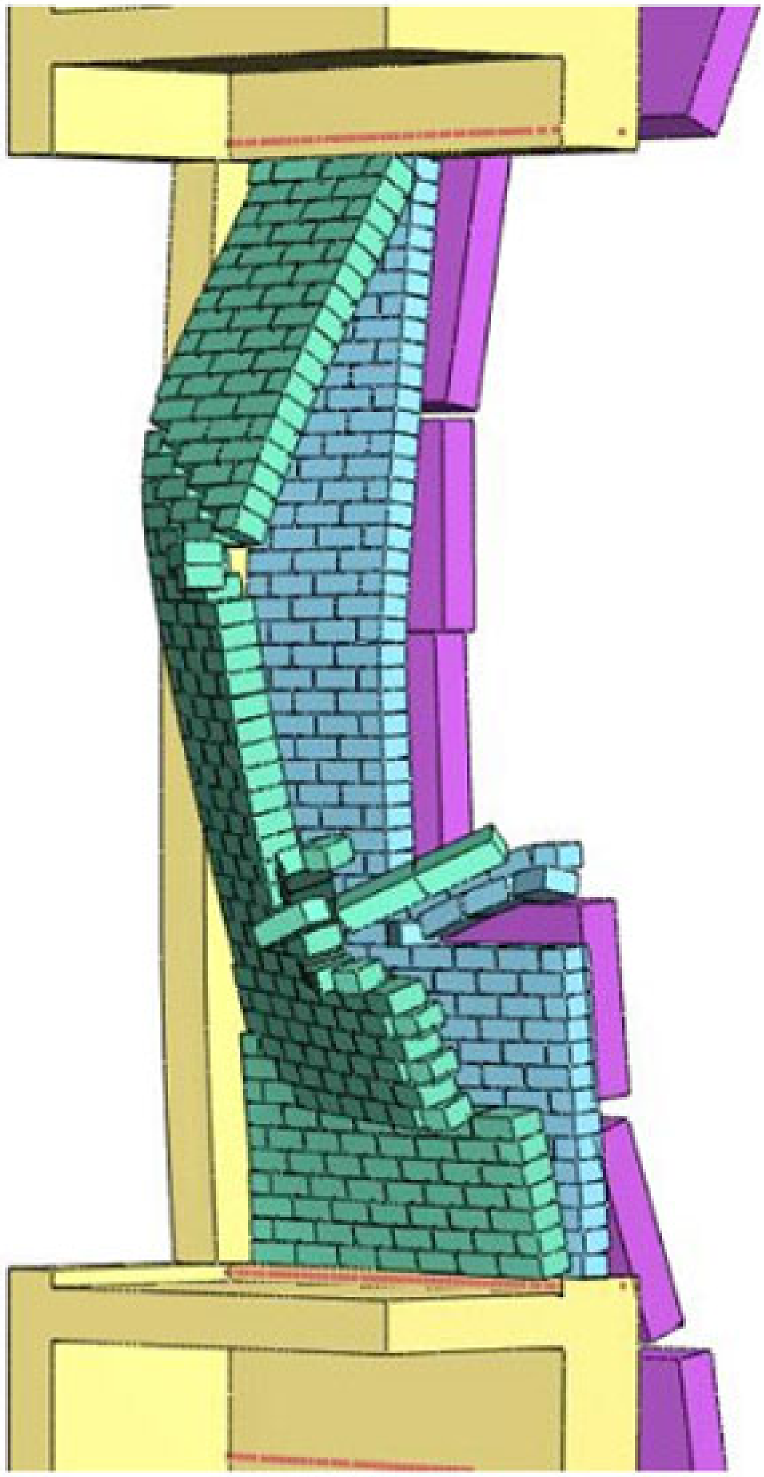

Figure 15. Failed original Pentagon wall model

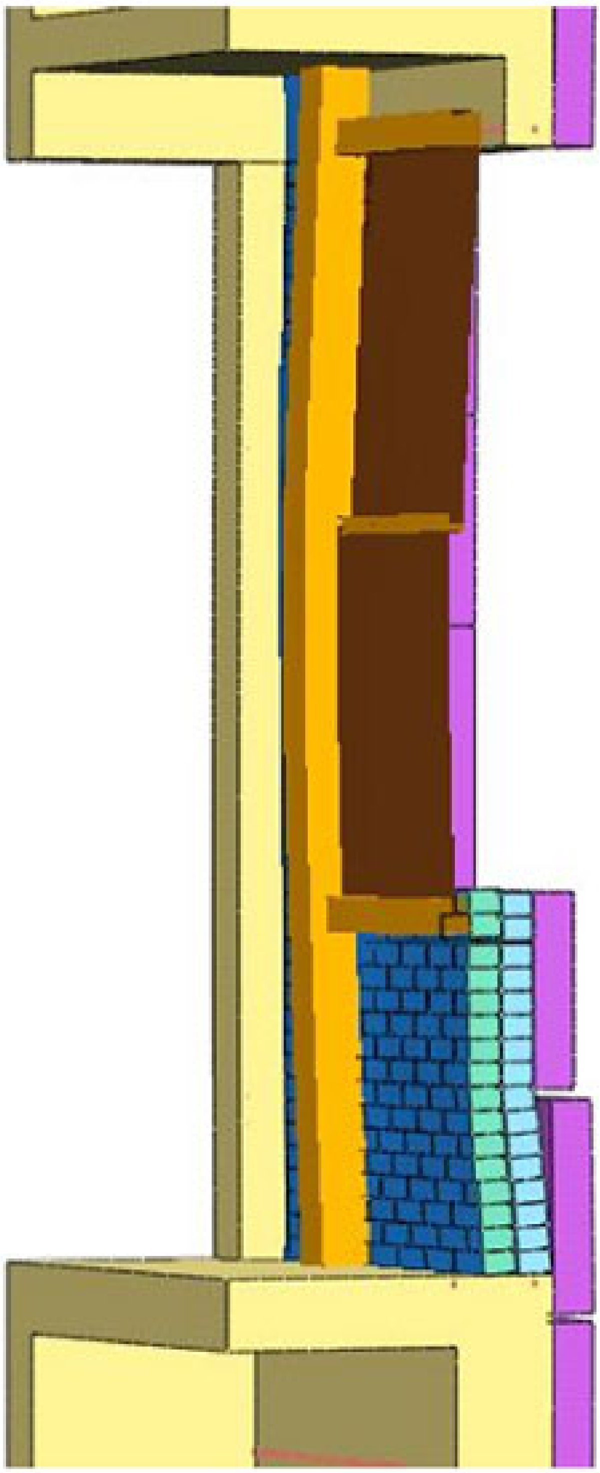

Figure 16. Successful wall retrofit

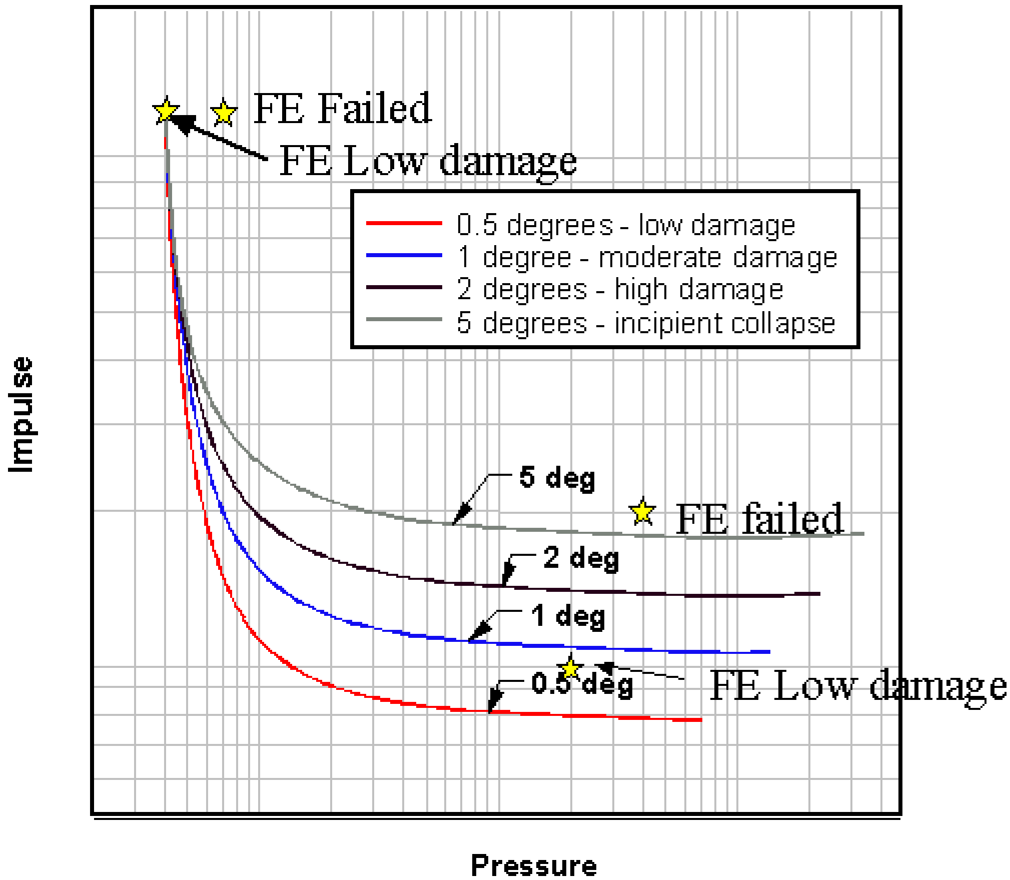

Figure 17. P-I diagram for original Pentagon wall

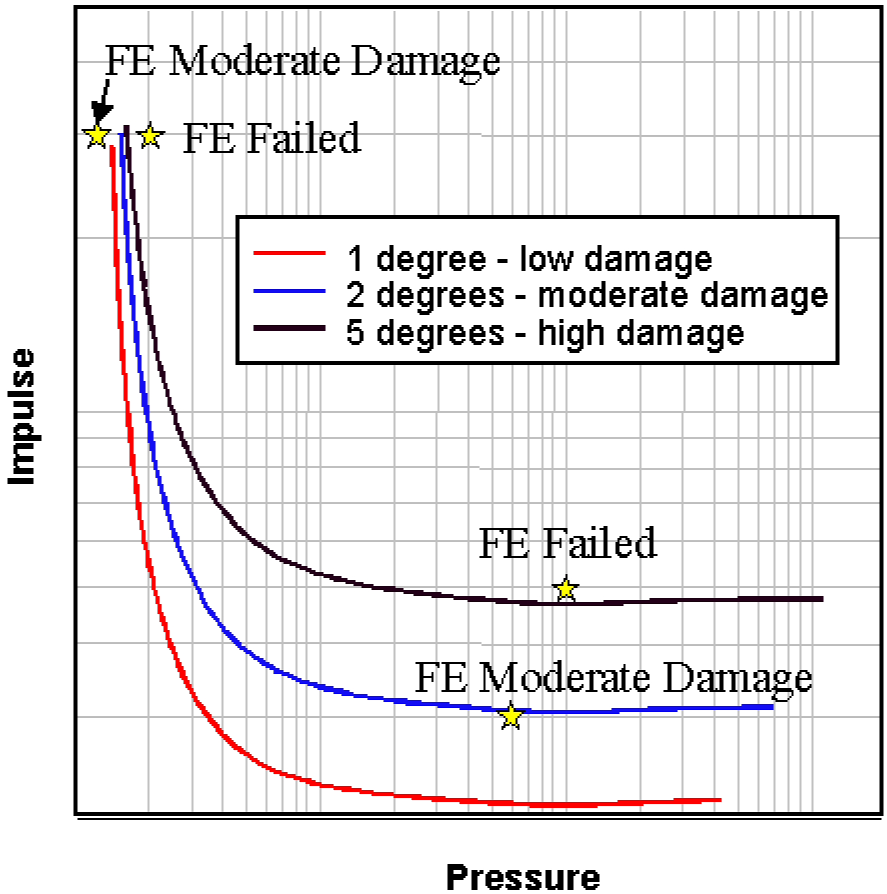

Figure 18. P-I diagram for original Pentagon retrofit

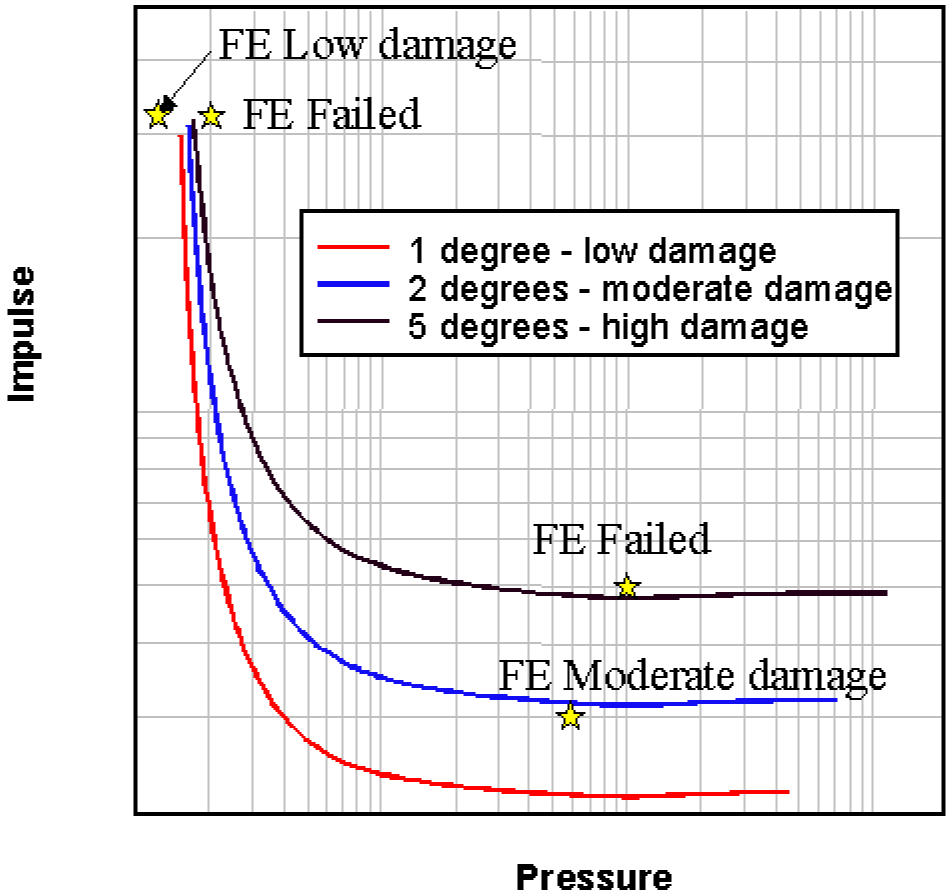

Figure 19. P-I diagram for first modified Pentagon retrofit

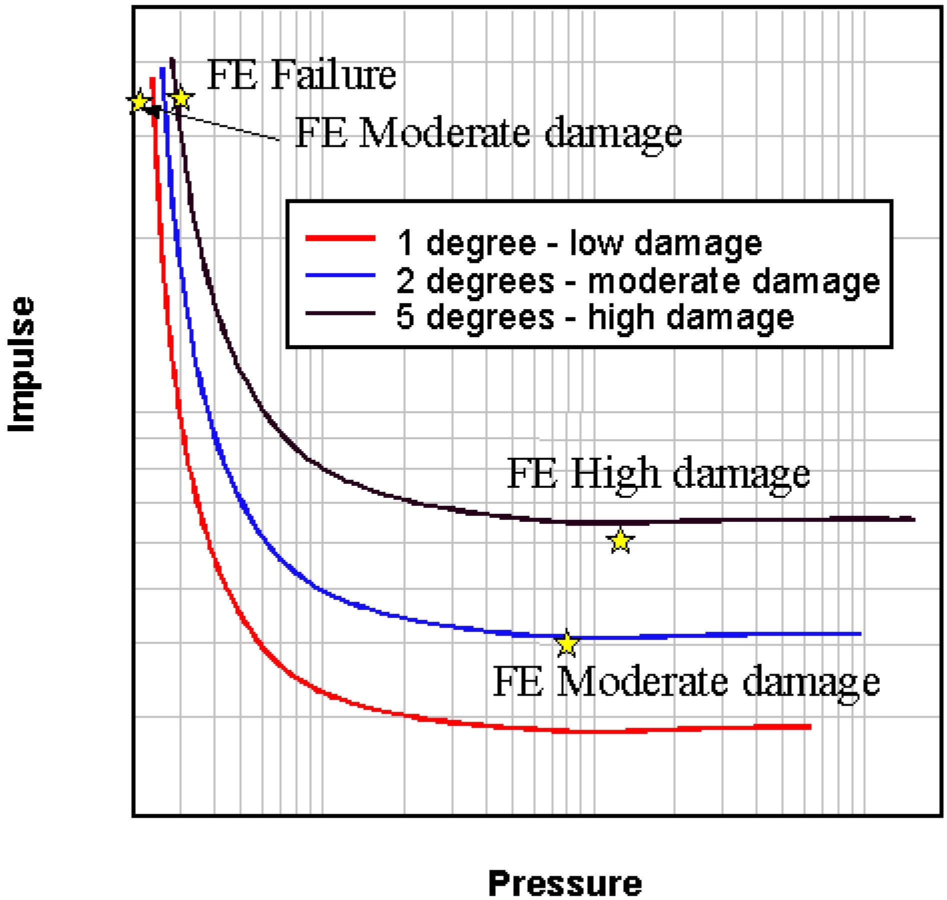

Figure 20. P-I diagram for second modified Pentagon retrofit

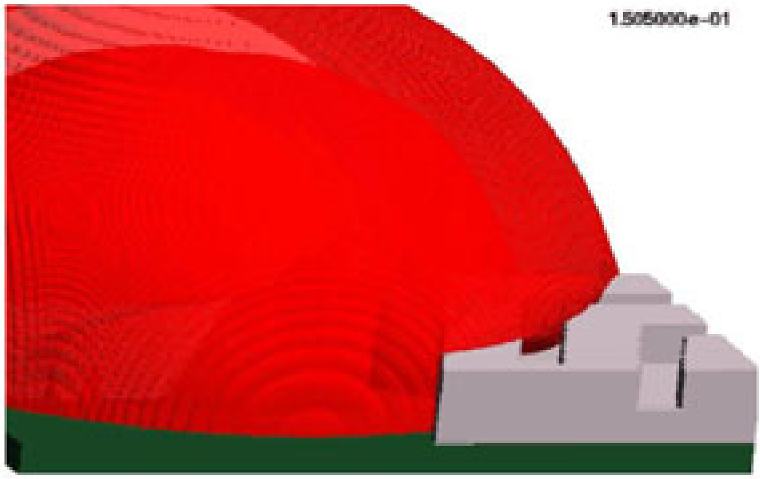

Figure 21. Blast propagation into lightwells